Enhancing the Conceptual Understanding of Science

by Dorothy Gabel

The objectives of science instruction at all levels should be conceptual understanding and scientific inquiry. Unfortunately, certain segments of the population equate science achievement with how well students score on science exams (Goodlad 1998). These tests frequently contain factual multiple-choice questions for which students have (or have not) memorized answers. Science reduced to a rote level becomes boring, and learning becomes a chore.

Many of the examples used in this article draw on my experiences of teaching chemistry at the elementary, secondary, and college levels. However, some applications may be readily adaptable to other areas of science.

Science can be understood at three different levels, each increasingly complex: the phenomena (macroscopic), the particle (microscopic), and the symbolic (Johnstone 1991). Consider water. Most two-year-old children can recognize and name the colorless, odorless liquid in a glass as water because they know the properties of the phenomenon water. A second way to understand water is to represent it as a collection of particles (molecules) that have attractive forces between them and that consist of the atomic particles hydrogen and oxygen. This mode of representation is certainly more complex than focusing on the physical properties of water. A third way of representing water is by using the symbols for hydrogen and oxygen to represent the formula H2O. In addition, symbolic mathematical formulas can be used to show properties of water. For example, the density of water equals mass/volume or $D = M/V = 1.0$ g/mL at 1 atm and 4ºC.

Students with a sound conceptual understanding of water integrate these three ways of representing water into long-term memory. During the learning process students' existing mental models must be modified for internal consistency and reconciled with scientists' understanding of the phenomena (Glynn and Duit 1995). One of the perplexing problems in teaching science is that textbooks contain more information than students can be expected to understand. When I took high school chemistry in the early 1950s, the text (Hogg, Alley, and Bickel 1948) contained 550 pages and 155 terms in the glossary. A more recent chemistry text (Dorin, Demmin, and Gabel 1992) contains 800 pages and 566 terms.

Twenty years ago, the two-time Nobel Prize winner Linus Pauling brought this information overload to our attention (1983), but his comments were ignored. Pauling said, "I think that we shall have much more success in teaching elementary [high school] chemistry when the textbooks contain 200,000 or 300,000 words instead of 500,000 to 600,000; when molecular-orbital theory and other confusing aspects of chemistry are left out of the books completely; when books weigh half as much as they do now. . . ." We must ask ourselves, Are students today more brilliant than they were in the past? Do they spend more time studying outside the classroom than they did twenty years ago? Is teaching more efficient today, so that students can learn as much science in 200 minutes per week as compared to 275 minutes per week in the 1960s? No, no, and no.

If we want to improve the conceptual understanding of science, teachers must be selective in the concepts they include in instruction. Much depends on the background that students bring to the course. This means not that more content should be moved to lower grade levels but that the *National Science Education Standards* (1995) should be used as a guide to provide reasonable levels of content. The *Standards* carefully delineate what leading experts in the field deem appropriate for most students at each grade level. Increasing the content may force students to memorize and turn out to be detrimental to conceptual understanding.

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Promoting the Conceptual Understanding of Science

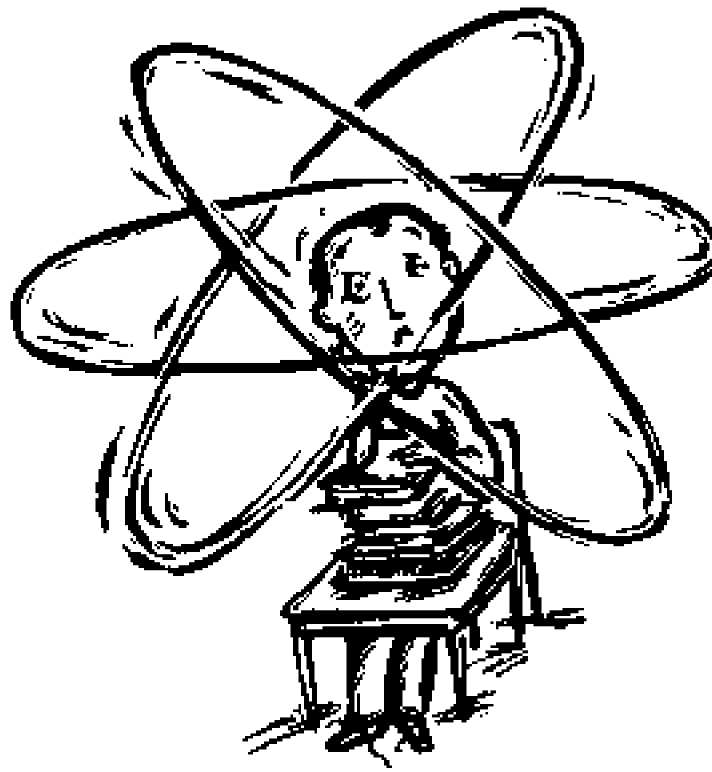
Sifting through decades of research, I identified (Gabel 1999) several effective strategies for learning in science. These include:

- Learning Cycle Approach
- Science/Technology/Society
- Real-Life Situations
- Discrepant Events
- Analogies
- Collaborative Learning
- Wait-Time
- Concept Mapping
- Inquiry
- Mathematical Problem Solving

These teaching strategies can be incorporated into various teaching-learning situations. One or two references are provided for each strategy.

Learning Cycle Approach

The Learning Cycle Approach involves three phases: exploration, invention, and application. Its application produces better content achievement, improved thinking skills, and more positive attitudes toward science. The first use of the Learning Cycle Approach began in the 1970s with the implementation of the NSF-funded elementary program, *Science Curriculum Improvement Study* (SCIS). The approach has been adapted for use in high school chemistry. The exploration phase includes providing students with items that they use to explore a given concept with few directives. For example, in one SCIS lesson for children at the primary level, children are given a tray containing several objects (water in a clear cup, a battery, scissors, paper clips, paper, a small light bulb, tiny colored candy balls, a rubber band, a magnet, and charcoal) with which they experiment and note what happens as they interact with the objects. An interactive teacher-centered phase describing relevant concepts follows. After students understand the concept, they apply it to a new situation in the application phase. The addition of a prediction phase before the exploration, and an evaluation phase after the application, makes the Learning Cycle Approach even more effective. For additional information about the Learning Cycle Approach see Lawson, Abraham, and Renner (1989).



Science/Technology/Society (STS)

STS is an approach to teaching science that includes developing an appreciation of the interactive natures of science, technology, and society. STS integrates science concepts with knowledge of technology and fosters an awareness of societal implications. Although there is little evidence that students' knowledge of facts, concepts, and principles increases when STS is a major thrust for instruction (not merely presented in vignettes), still positive outcomes occur. Students learn to analyze data and test hypotheses, use their creativity, and develop positive attitudes toward science. A student who has developed an interest in science is more likely to take additional courses.

A good example of an STS unit is found in the high school chemistry text *Chemistry in the Community* (2001). At the end of Unit 5, "Industry: Applying Chemical Reactions," students participate in a "town meeting," where they debate the merits of building chemical plants on a river that runs through their town. They apply their knowledge of chemistry, acquired by studying previous chapters, to a real-life situation that might affect their water quality.

Through STS, students learn about the nature of science, scientific inquiry, and good citizenship—benefits that supersede what is normally considered to be the science curriculum. Whereas the Learning Cycle Approach is more commonly used in elementary schools, the STS approach is more common in secondary schools. More information on STS instruction can be found in Yager (1996).

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Real-Life Situations

Other science instruction has been designed using real-life situations that do not necessarily include technological or societal problems. Research supports programs that use videotapes, CD-ROMs, and videodiscs. These programs not only increase students' knowledge of facts and concepts but also, it has been found, improve problem-solving skills and increase interest in science.

Computer simulations are one way of representing real-world situations. Not only can a computer simulate what is happening on the macroscopic level; its models can show what occurs on the particle level. One possible danger in using simulations in chemistry is that they can lead to misconceptions. For example, the simulations might convince students that atoms are hard, colored balls. Even though balls can be arranged in certain patterns to form molecules, more accurate models of atoms and molecules are available. Unfortunately, many students do not realize that the balls are only models and that individual atoms do not have the properties of the macroscopic material they represent.

A major focus of using real-life situations is to improve students' problem-solving skills, and evidence indicates that the approach is successful. The leading research group in the United States studying the effectiveness of anchored learning is located at Vanderbilt University (Cognition and Technology Group at Vanderbilt 1993). For use of the computer in instruction, see Lehman (1994).

Discrepant Events

In a discrepant event, anomalous data are presented to students, usually by a demonstration. First, students are asked to predict what they expect to happen before a demonstration and explain why they think it should happen that way. Then they observe what happens and are asked to modify their previous explanation. In the Learning Cycle Approach, the exploration phase can be set up so that students encounter discrepant events.

An example of a discrepant event that could be used at the beginning of a unit on energy is to ask the students to predict the temperature of a pencil and the temperature of the metal arm on their chairs before measuring the temperatures of each with a thermometer. Most will use their experience to predict that the wood of the pencil will have a higher temperature than the metal. They will be unable to explain why. When they place the thermometer on the two objects, they are surprised that the temperatures are the same. The unit on energy begins with a discussion of heat versus temperature, and uses the discrepant event as a springboard.

Although there is little evidence that using discrepant events promotes conceptual understanding in itself, it does help students analyze their thought processes. It is difficult to test the effectiveness of using discrepant events because they may not be used consistently throughout a course. Chinn and Brewer (1993) provide additional information on using anomalous data in science instruction.

Analogies

Using analogies in science teaching promotes conceptual understanding. By comparing the scientific principle under scrutiny with one that is familiar, a student can gain a better understanding of the principle. For example, if a chemistry teacher wants students to understand factors that speed up chemical reactions, she could compare the collisions of molecules that occur in a chemical reaction to the collision of cars in a traffic accident. The more moving cars on the road, the more collisions; the greater the concentration of molecules in a solution, the more frequent the collisions. Likewise, if cars move faster, the amount of damage increases; when molecules move faster by heating the chemicals, the reaction rate increases. In using an analogy, care must be taken to make certain that students know the limitations of the analog. In this case, molecules certainly do not look like autos. Autos move by the burning of gasoline. Molecules move faster when they are heated to higher temperatures.

Wong (1993) provides additional information on using analogies in science instruction.

Collaborative Learning

Collaborative learning, in which students work in groups to solve problems, perform laboratory exercises, or participate in projects, has positive effects on achievement. Cooperative learning is quite different from the teaching techniques discussed previously because it relies upon social interactions among students. Collaborative learning can be incorporated into the Learning Cycle and STS strategies, and it may contribute to their effectiveness. Popular in elementary schools since the mid-1960s, collaborative learning has recently regained popularity in secondary schools.

Some collaborative groups are highly structured. For example, in the "jigsaw approach" the class is divided into groups of four or five students. Each student in the group is assigned a particular question about a topic to be studied. Students studying the same topic assemble into new groups, discuss how they will answer the question, complete the research, and discuss the results. Students then return to their original groups and teach the other students the findings of their previous groups. In this way every student learns one topic in depth and the other topics in a more general way. If the topic is water pollution, each group in a class can explore a different question, such as the causes of water pollution, how water can be purified, pollution's effect on aquatic life, or how pollution can be prevented.

Since the 1980s, the technique of giving an individual student a specific role has been used in laboratory instruction. A group of four can have a facilitator, an experimenter, a recorder, and an equipment manager. Roles rotate for each laboratory investigation.

A third form of collaborative learning that has become more prominent in the past few years is the use of ConcepTests. This technique, created by Eric Mazur for instruction in an introductory physics course at Harvard University, can be used in large lectures by students working with their nearest neighbor, or in smaller classroom settings with three or four students per group. A ConcepTest usually consists of a single, multiple-choice item on one concept (Mazur 1997).

On a ConcepTest, the correct answer requires conceptual understanding rather than a memorized response. After the question is posed, students are given a minute to think. Then they record their individual answers, try to convince their neighbors, and record their revised answers. Their instructor asks for the revised answers and explains the correct solution. By monitoring the class during the exercise, the instructor can determine the misconception, difficulty, and concept attainment of the students. ConcepTests can be built into almost any science course, and when used consistently, enhance conceptual understanding.

The use of collaborative learning frequently results in increased achievement scores, long-term retention, higher self-esteem, increased conceptual understanding, and more adept problem-solving ability. Additional information on cooperative learning can be found in Lazarowitz and Hertz-Lazarowitz (1998).

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Wait-Time

"Wait-time" refers to the time that an instructor waits to call on a student for a response after posing a question. It also involves withholding whether the answer given is correct before calling on another student to respond. The technique of waiting between three and seven seconds after asking the students a higher-level question provides time for thinking. Allowing sufficient wait-time also seems to increase the length of student comments, the frequency of questions, the number of responses from less-capable children, and the incidence of speculative responses. Mary Budd Rowe's extensive research on wait-time found that increased wait-time can positively affect achievement, particularly on higher-level test items, in both elementary and secondary classrooms. Additional information about wait-time is available in Rowe (1986).

Concept Mapping

Another successful technique that improves understanding of science is concept mapping. Concept maps are schematic diagrams that use

words to show the relation of one concept to another. For example, Herron's map (1996) of an ideal gas begins with three main concepts—pure, volume, and molecules—that are subsequently linked to three other concepts. These are linked further, resulting in a map of seventeen concepts.

A comprehensive conceptual understanding of an ideal gas would involve knowing all the relationships depicted in the diagram. However, this does not mean that students should memorize the map. In fact, if other experts were asked to make maps of an ideal gas, their maps would likely look different. Teachers can use concept maps in planning their lessons to make certain that appropriate subconcepts are included. They may also ask students to make concept maps before instruction to determine their conceptual understanding of subconcepts on which to build lesson plans. During instruction, the use of concept maps requires students to focus on the relationships among concepts. After instruction, teachers can ask students to make concept maps of the topic studied to determine if they have grasped the relationship or if additional instruction is needed.

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A modified form of concept maps (also called strand maps) has been published in the *Atlas of Scientific Literacy* by the American Association for the Advancement of Science (1991). This book provides complex maps devised by scientists and science educators of many of the common topics studied in schools. It is an excellent resource to help curriculum developers and textbook authors determine the structure of topics for instruction.

Concept mapping helps students focus on the relationships among concepts so that students' long-term memories will accord with the scientific view. Concept mapping can be a boring exercise, but it can be effective when used with other teaching techniques. Additional information on concept maps is available in Ruiz-Primo and Shavelson (1996).

Inquiry

Scientists frequently ask questions as hypotheses and then use certain processes (such as making observations, inferences, or predictions; classifying; controlling variables; measuring; and making charts and graphs) to draw conclusions. Students can use inquiry not only to deepen their conceptual understanding of a given topic, but also to learn the same processes that scientists use in discovering new knowledge. Inquiry was thought to be such an essential component of science instruction in K–12 schools that it is stressed in the *National Science Education Standards* (1995). In fact, a companion book, *Inquiry and the National Science Education Standards,* was published in 2000.

Many different meanings have been given to "scientific inquiry." Inquiry means more than conducting laboratory experiments or hands-on activities, although both can be structured as inquiry experiences. Inquiry involves answering questions about the world in which we live. The essential features of classroom inquiry, as presented in *Inquiry and the National Science Education Standards*, include engaging students through scientifically oriented questions; obtaining evidence related to the questions; formulating explanations from the evidence; evaluating the explanations in light of other possible explanations; and communicating and justifying their explanations to others.

At present, laboratory exercises in schools frequently consist of verification activities that require little analysis. Their purpose is to confirm facts and concepts discussed in the text. There is nothing wrong with such an approach; most students enjoy the laboratory exercises and may learn something of value. They do not, however, learn much about how scientists set out to investigate hypotheses.

According to Sutman (1997), the processes involved in inquiry include pre-laboratory experience, laboratory experience, and post-laboratory experience. At the highest level of inquiry, students should initiate and complete the whole process. Unfortunately, most laboratory instruction rarely includes post-laboratory dialogue.

It is interesting to note that an attempt to bring high school chemistry students to this threshold was made during the post-Sputnik era. *Investigating Chemical Systems,* the laboratory manual of the *Chemical Bond Approach Project* (1963), begins with structured experiments that become increasingly less directed as the course progresses. The last experiment, "Experiment 46" (p. 69), contains no title or hint of what

should be investigated. Students are expected to create a hypothesis, carry out an investigation, report findings, and give explanations. I have never seen a report on how many students were assigned "Experiment 46." The curriculum was not widely used because many teachers thought the material was too difficult for average high school students.

The process of inquiry is evident when students undertake self-initiated science-fair projects based on hypotheses that they formulate rather than on demonstrations. Some science teachers have also implemented project-based learning in their classrooms. Although not a part of the everyday curriculum, once or more during the semester students create hypotheses for which they collect and analyze data. Eventually, students present their findings to the class. Research on inquiry-based teaching indicates the technique produces modest gains in cognitive achievement, process skills, and attitudes toward science.

Additional information on inquiry learning is available in *Inquiry and the National Science Education Standards* (2000).

Mathematical Problem Solving

A discussion of conceptual understanding would be incomplete without a section on mathematical problem solving in the sciences. All sciences include mathematical models, and in almost every science course students are expected to make calculations. The question becomes whether mathematical problem solving leads to conceptual understanding. The answer is that it can lead to conceptual understanding, but that it also has the potential to hinder it.

Consider, for example, the concept of density. Density can be defined mathematically as mass/volume or $D = M/V$. Given the following problem—15 grams of an unknown liquid when poured into a graduated cylinder measures 10 mL—what is the density of the liquid? In order to solve the problem, the student would need to know the formula for density, that mass is measured in grams, that volume is measured in mL, and how to divide. The problem could have been made easier if that information was given in the problem. Even if a student arrived at the correct answer (1.5 g/mL), does this mean that the student understands the concept of density?

Students who use a memorized algorithm or dimensional analysis (factor-label method) frequently obtain correct answers. But a correct answer does not necessarily mean that students understand the concepts. Some instructors will argue that students using an algorithmic approach will eventually learn the concepts, but unfortunately, many students never reach the conceptual level of understanding.

Research on mathematical problem solving shows that a systematic approach to problem solving results in more correct answers. However, another approach might be to spend more time emphasizing the qualitative aspects of the concepts before introducing quantitative problem solving. If students view understanding chemistry and physics as applying formulas to solve problems, little will be gained in terms of conceptual understanding.

Summary and Implications

Teaching science for understanding is a complex issue. It involves learning the macroscopic properties of phenomena, explaining the macroscopic phenomena and processes using models, using symbols in mathematical problem solving, and understanding the processes that scientists use in inquiry. For instruction to be effective, science needs to be presented in an organized hierarchy so that one concept builds upon another. There is probably no single hierarchy that is most efficient for learning for all students.

Teaching programs that consistently use a more comprehensive approach, such as that employed in the Learning Cycle Approach and STS, may be more successful because they show students the relevance of what they are learning. Science educators must continue to explore ways not only of improving students' understanding of science but of helping them to see its relevance in today's world.

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